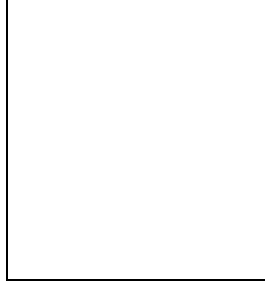# THE BARYON BUDGET FROM BBN AND THE CBR

GARY STEIGMAN

Department of Physics, The Ohio State University,
174 West 18th Avenue
Columbus, OH 43210, USA

A key pillar of modern cosmology, Big Bang Nucleosynthesis (BBN) offers a probe of the particle content and expansion rate of the Universe a mere few minutes after the beginning. When compared with the BBN predictions, the observationally inferred primordial abundances of deuterium and helium-4 provide an excellent baryometer and chronometer respectively. Several hundred thousand years later, when the Cosmic Background Radiation (CBR) photons began progagating freely, the spectrum of temperature fluctuations imprinted on them also encoded information about the baryon density and the expansion rate. Comparing the constraints imposed by BBN with those from the CBR reveals a consistent picture of the Universe at these two very widely separated epochs. Combining these probes leads to new, tighter constraints on the baryon density at present and on possible new physics beyond the standard model of particle physics.

1   Introduction

As the hot, dense, early Universe rushed to expand and cool, it briefly passed through the epoch of big bang nucleosynthesis (BBN), leaving behind as relics the first complex nuclei: deuterium, helium-3, helium-4, and lithium-7. The abundances of these relic nuclides were determined by the competition between the relative densities of nucleons (baryons) and photons and also by the universal expansion rate. In particular, while deuterium is an excellent baryometer, ^{4}He provides an accurate chronometer. Nearly 400 thousand years later, when the cosmic background radiation (CBR) had cooled sufficiently to allow neutral atoms to form, releasing the CBR from the embrace of the ionized plasma of protons and electrons, the spectrum of temperature fluctuations imprinted on the CBR preserved the values of the contemporary baryon and radiation densities, along with the universal expansion rate at that epoch. As a result, the relic abundances of the light nuclides and the CBR temperature fluctuation spectrum provide

invaluable windows on the early evolution of the Universe as well as sensitive probes of its particle content.

The fruitful interplay between theory and data has been key to the enormous progress in cosmology in recent times. As new, more precise data became available, models have had to be rejected or refined. It is anticipated this this process will – indeed, should – continue. Therefore, this review of the baryon content of the Universe as revealed by BBN and the CBR is but a signpost on the road to a more complete understanding of the history and evolution of the Universe (for a related review, with more detailed discussion and a more extensive bibliography, see Steigman [1]). By highlighting the current successes of the present "standard" model along with some of the challenges to it, I hope to identify those areas of theoretical and observational work which will contribute to progress towards the goal of understanding the Universe, its past, present, and future.

2 BBN And The Baryon Density

The hot, dense, early Universe is a hostile environment for complex nuclei. At sufficiently high temperatures ($T \gtrsim 80$ keV), when all the nucleons (baryons) were either neutrons or protons, their relative abundance was regulated by the weak interaction; the higher mass of the neutron ensures that protons dominate (in the absence of a chemical potential for the electron-type neutrinos ν_e). Below ~ 80 keV, the Universe has cooled sufficiently that the cosmic nuclear reactor can begin in earnest, building the lightest nuclides D, ^{3}He, ^{4}He, and ^{7}Li. Very rapidly, D and ^{3}He (also ^{3}H) are burned to ^{4}He, the most tightly bound of the light nuclides. The absence of a stable mass-5 nuclide ensures that in the expanding, cooling, early Universe, the abundances of heavier nuclides are greatly suppressed. By the time the temperature has dropped below ~ 30 keV, a time comparable to the neutron lifetime, the average thermal energy of the nuclides and nucleons is too small to overcome the coulomb barriers, any remaining free neutrons decay, and BBN ceases.

In the expanding Universe the number densities of all particles decrease with time, so that the magnitude of the baryon density (or that of any other particle) has no meaning without also specifying *when it is measured*. To quantify the universal abundance of baryons, it is best to compare the baryon number density n_B to the CBR photon number density n_γ. After $e^\pm$ pairs have annihilated the ratio of these number densities remains effectively constant as the Universe evolves. This ratio $\eta \equiv n_B/n_\gamma$ is very small, so that it is convenient to define a quantity of order unity,

$$\eta_{10} \equiv 10^{10}(n_B/n_\gamma) = 274\,\Omega_B h^2, \tag{1}$$

where Ω_B is the ratio (at present) of the baryon density to the critical density and h is the present value of the Hubble parameter in units of 100 km s^{-1} Mpc^{-1}. The relic abundances of D, ^{3}He, and ^{7}Li shown in Figure 1 are *rate limited*, determined by the competition between the early Universe expansion rate and the nucleon density. Any of these three nuclides is a potential baryometer.

In contrast to the synthesis of the other light nuclides, once BBN commences the reactions building ^{4}He are so rapid that its relic abundance is not rate limited but, rather, is limited by the availability of neutrons. To a very good approximation, the relic abundance of ^{4}He is set by the neutron abundance at the beginning of BBN. The neutron abundance (relative to protons) is determined by the competition between the universal expansion rate (the Hubble parameter, H) and the weak interaction rates ($p + e^- \longleftrightarrow n + \nu_e,\ n + e^+ \longleftrightarrow p + \bar{\nu}_e,\ n \longleftrightarrow p + e^- + \bar{\nu}_e$), which are well constrained (in the absence of large ν_e chemical potentials) by the neutron lifetime ($\tau_n = 885.7 \pm 0.8$ s). As a result, the primordial mass fraction of ^{4}He, Y$_P$, while a relatively insensitive baryometer (see Figure 1), is an excellent, early-Universe chronometer.
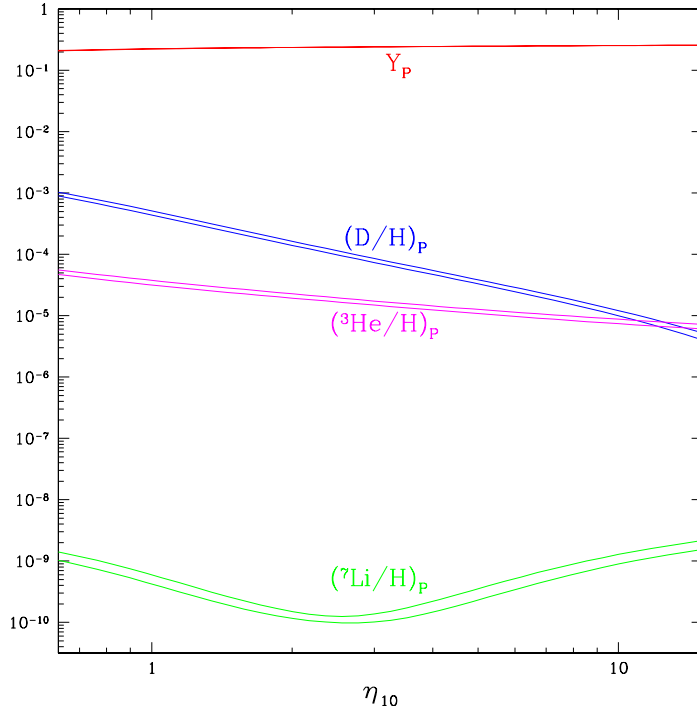
Figure 1: The SBBN-predicted primordial abundances of D, ^{3}He, and ^{7}Li by number with respect to hydrogen, and the ^{4}He mass fraction Y_P, as a function of the nucleon (baryon) abundance parameter η_{10}. The bands reflect the theoretical uncertainties ($\pm 1\sigma$) in the BBN predictions.

The expansion rate (measured by the Hubble parameter H) is related to the energy density through the Friedman equation ($H^2 = \frac{8\pi G}{3}\rho$). During BBN the Universe is "radiation-dominated" (RD); the energy density (ρ_R) is dominated by the relativistic particles present. For the standard model (SBBN) there are three families of light (relativistic) neutrinos ($N_\nu = 3$). To explore models with nonstandard, early (RD) expansion rates it is convenient to introduce the *expansion rate factor* $S \equiv H'/H = t/t'$. One possible origin for a nonstandard expansion rate ($S \neq 1$) is a modification of the energy density by the presence of "extra" relativistic particles X: $\rho_R \rightarrow \rho'_R = \rho_R + \rho_X$. If the additional energy density is normalized to that which would be contributed by additional flavors of (decoupled) neutrinos (Steigman, Schramm, & Gunn [2]), $\rho_X \equiv \Delta N_\nu \rho_\nu$, then $N_\nu = 3 + \Delta N_\nu$. It must be emphasized that the fundamental physical parameter is S, the expansion rate factor, which may be related to ΔN_ν (*nonlinearly*) by

$$S_{pre} \equiv (H'/H)_{pre} = (1 + 0.163\Delta N_\nu)^{1/2}; \quad S_{post} \equiv (H'/H)_{post} = (1 + 0.135\Delta N_\nu)^{1/2}, \quad (2)$$

where the subscripts "*pre*" and "*post*" reflect the values prior to, and after $e^\pm$ annihilation respectively. However, any term in a modified (nonstandard) Friedman equation which scales like radiation (decreases as the fourth power of the scale factor), such as may be due to higher dimensional effects as in the Randall-Sundrum [3] model, will change the standard-model expansion rate ($S \neq 1$) and may be related to an *equivalent* ΔN_ν (which may be *negative* as well as positive; both $S > 1$ and $S < 1$ are possible) through Eq. 2.

The qualitative effects of a nonstandard expansion rate on the relic abundances of the light nuclides may be understood with reference to Figure 1. For the baryon abundance range of interest ($1 \lesssim \eta_{10} \lesssim 10$) the relic abundances of D and ^{3}He are decreasing functions of η, revealing that in this range D and ^{3}He are being destroyed. A faster than standard expansion ($S > 1$) leaves less time for this destruction so that more D and ^{3}He would survive. The same is true

for ^{7}Li for low values of η, where the abundance of ^{7}Li is a decreasing function of η. However, at higher values of η, where the ^{7}Li abundance increases with η, less time available results in less production and a *smaller* ^{7}Li relic abundance. Except for dramatic changes to the early-Universe expansion rate, these effects on the relic abundances of D, ^{3}He, and ^{7}Li are subdominant to their dependences on the baryon density. Not so for ^{4}He, whose relic abundance is very weakly (logarithmically) dependent on the baryon density, but very strongly dependent on the early-Universe expansion rate. A faster expansion leaves more neutrons available to be incorporated into ^{4}He; to a good approximation, $\Delta Y \approx 0.16\,(S-1)$. It is clear then that if ^{4}He is paired with any of the other light nuclides, together they can constrain both the baryon density ($\Omega_B h^2$ or η) and the early-Universe expansion rate (S or ΔN_ν).

3   The Best BBN Baryometer?

At present, deuterium is the baryometer of choice. As the Universe evolves, structure forms, and gas is cycled through stars. Because of its very low binding energy, deuterium is completely destroyed in any gas which passes through stars; in the post-BBN Universe the D abundance never exceeds that emerging from BBN. Because the evolution of D is simple, monotonically decreasing since BBN, observations of D anywhere, anytime, yield a lower bound to its primordial abundance. Observations of D in "young" systems (high redshift or low metallicity), should reveal a deuterium "plateau" at its primordial abundance. In addition to its simple post-BBN evolution, deuterium is the baryometer of choice also because its primordial abundance ($y_D \equiv 10^5(D/H)_P$) is sensitive to the baryon density, $y_D \propto \eta^{-1.6}$; as a result, a $\sim 10\%$ measurement of y_D will lead to a $\sim 6\%$ determination of η (or $\Omega_B h^2$).

In contrast to D, the post-BBN evolution of ^{3}He and ^{7}Li are complex. For example, ^{3}He is destroyed in the hotter interiors of all but the least massive stars, but is preserved in the cooler, outer layers of most stars. In addition, hydrogen burning in low mass stars results in the production of significant amounts of *new* ^{3}He [4]. To follow the post-BBN evolution of ^{3}He, it is necessary to account for all these effects – quantitatively – in the material returned by stars to the interstellar medium (ISM). As indicated by the existing Galactic data [5], a very delicate balance exists between net production and net destruction of ^{3}He in the course of the evolution of the Galaxy. Thus, aside from noting the excellent qualitative agreement between the SBBN prediction and the observed ^{3}He abundances, ^{3}He has little role to play, at present, as a quantitatively useful baryometer. A similar scenario may be sketched for ^{7}Li. As a weakly bound nuclide, it is easily destroyed when cycled through stars. The high lithium abundances observed in the "super-lithium-rich red giants" provide direct evidence that at least some stars do produce post-BBN lithium, but a key unsolved issue is how much of this newly-synthesized lithium is actually returned to the ISM. Furthermore, the quest for observations of nearly primordial lithium is limited to the oldest, most metal-poor stars in the Galaxy, stars that have had the most time to redistribute – and destroy or dilute – their surface lithium abundances. At present it seems that the most fruitful approach is to use the BBN-predicted lithium abundance, compared to that inferred from observations of the oldest stars, to learn about stellar evolution rather than to use stellar observations to constrain the BBN-inferred baryon density.

3.1   Deuterium

In pursuit of the most nearly primordial D abundance, it is best to concentrate on "young" systems, in the sense of those which have experienced the least evolution. Thus, while observations of D in the solar system and/or the local ISM provide useful *lower* bounds to the primordial D abundance, it is observations of deuterium (and hydrogen) absorption in a handful (so far) of
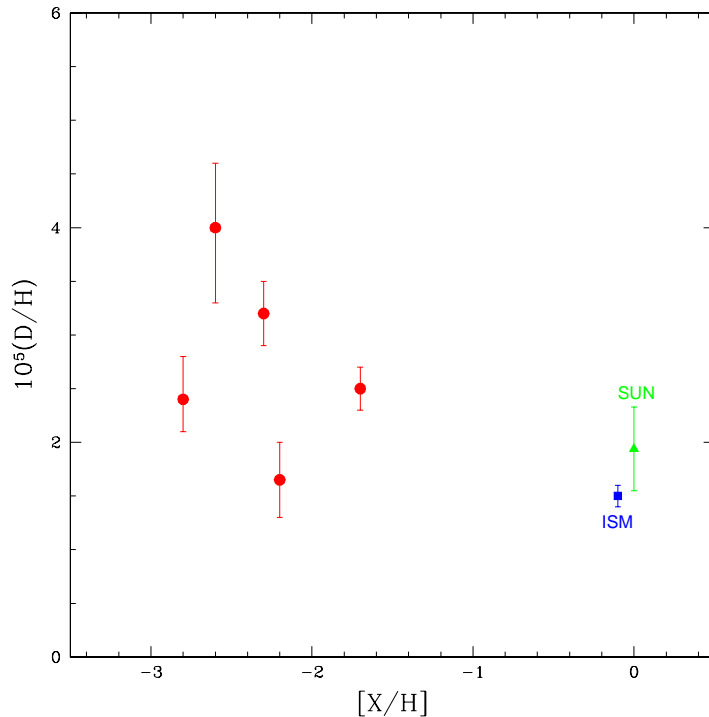
Figure 2: The deuterium abundance by number with respect to hydrogen, versus the metallicity (relative to solar on a log scale), from observations (as of early 2003) of QSOALS (filled circles). "X" is usually Si. Also shown for comparison are the D abundances for the local ISM (filled square) and the solar system ("Sun"; filled triangle).

high redshift, low metallicity, QSO absorption-line systems (QSOALS) which provide the most relevant data. However, inferring the primordial D abundance from the QSOALS has not been straightforward, with some abundance claims having been withdrawn or revised. Presently there are only five QSOALS with reasonably firm deuterium detections[6]; the derived abundances of D are shown in Figure 2 along with the corresponding solar system and ISM D abundances.

As is clear from Figure 2, there is significant dispersion among the derived D-abundances at low metallicity. The data fail to reveal the anticipated deuterium plateau, suggesting that systematic errors may be present, contaminating some of the determinations of the D I and/or H I column densities. Since the D I and H I absorption spectra are identical, except for the wavelength/velocity offset resulting from the heavier reduced mass of the deuterium atom, an H I "interloper", a low-column density cloud shifted by ~ 81 km s^{-1} with respect to the main absorbing cloud, would masquerade as D I. If this is not accounted for, a D/H ratio which is too high would be inferred. Since there are more low-column density absorbers than those with high H I column densities, absorption-line systems with somewhat lower H I column density (e.g., Lyman-limit systems) are more susceptible to this contamination than are the higher H I column density absorbers (e.g., damped Lyα absorbers). However, for the damped Lyα absorbers, an accurate determination of the H I column density requires an accurate placement of the continuum, which could be compromised by interlopers. This might lead to an overestimate of the H I column density and a concomitant underestimate of D/H (J. Linsky, private communication). There is the possibility that each of these effects, separately or in combination, may have contaminated some of the current data, leading to the excessive dispersion seen in Figure 2 (provided there is, indeed, a true deuterium "plateau" at low metallicity). To utilize the current data I follow the lead of O'Meara et al. [6] and Kirkman et al. [6] and adopt for the primordial D abundance the weighted mean of the D abundances for the five lines of sight[6],
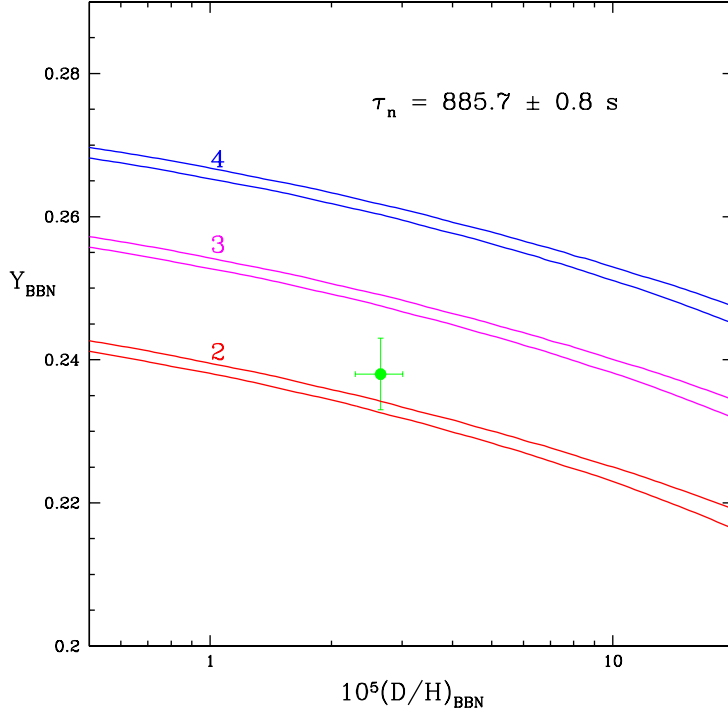
Figure 3: The BBN-predicted ^{4}He mass fraction Y_{BBN} versus the corresponding BBN-predicted deuterium abundance $y_D \equiv 10^5(D/H)_{BBN}$ for $N_\nu = 2$, 3, 4 (corresponding to $S = 0.915$, 1, 1.078). The data point (filled circle with error bars) is for the D and ^{4}He abundances adopted here (see the text).

while the dispersion in the data is used to set the error in y_D: $y_D = 2.6 \pm 0.4$. It is worth noting that for the same data Kirkman *et al.*[6] derive a slightly higher mean D abundance: $y_D = 2.74$. The difference is due to their first finding the mean of $\log(y_D)$ and then using it to compute the mean D abundance ($y_D \equiv 10^{\langle \log(y_D) \rangle}$).

4   Helium-4: The Best BBN Chronometer

While D, ^{3}He, and ^{7}Li are all potential BBN baryometers, the relic abundance of ^{4}He is too weakly dependent on the universal density of baryons to permit it to be used as a effective baryometer. However, the primordial abundance of ^{4}He is sensitive to the early-Universe expansion rate. The primordial ^{4}He mass fraction, Y_P, is the BBN chronometer of choice. The net effect of post-BBN evolution was to burn hydrogen to helium, increasing the ^{4}He mass fraction above its primordial value ($Y > Y_P$). As with D, although ^{4}He is constrained by solar system and ISM (Galactic H II regions) data, the key to the Y_P determinations are the observations of ^{4}He in nearly unevolved, metal-poor regions. To date they are limited to the observations of helium and hydrogen recombination lines in extragalactic H II regions[7]. Unfortunately, at present the H II region ^{4}He data has an even greater dispersion in the derived Y_P values than that for primordial D, ranging from $Y_P = 0.234 \pm 0.003$ to $Y_P = 0.244 \pm 0.002$, suggesting that current estimates are not limited by statistics, but by uncorrected systematic errors[8]. Here, I adopt the compromise proposed in Olive, Steigman, and Walker[9]: $Y_P = 0.238 \pm 0.005$; for further discussion and references, see Steigman[1].

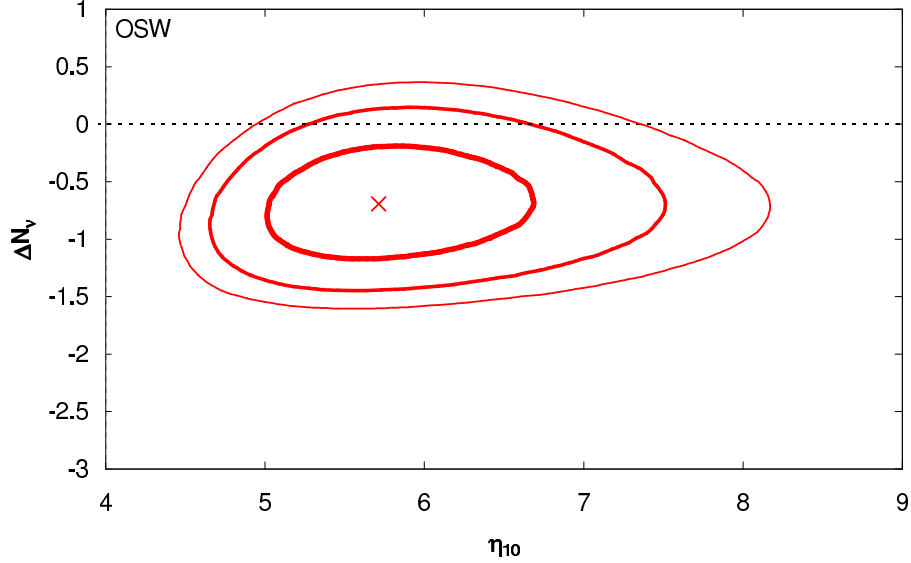Figure 4: The 1-, 2-, and 3-σ contours in the $\eta - \Delta N_\nu$ plane for BBN and the adopted D and ^{4}He abundances.

5   Testing BBN

For SBBN, the baryon density corresponding to the D abundance adopted here ($y_D = 2.6 \pm 0.4$) is $\eta_{10} = 6.1^{+0.7}_{-0.5}$, corresponding to $\Omega_B h^2 = 0.022^{+0.003}_{-0.002}$. This is in outstanding agreement with the estimate of Spergel *et al.* [10], based largely on the new CBR (*WMAP*) data (Bennett *et al.* [10]): $\Omega_B h^2 = 0.0224 \pm 0.0009$. For the baryon density determined by D, the SBBN-predicted abundance of ^{3}He is $y_3 = 1.0 \pm 0.1$, which is to be compared to the outer-Galaxy abundance of $y_3 = 1.1 \pm 0.1$, suggested by Bania, Rood, & Balser [5] to be nearly primordial. Again, the agreement is excellent; the concordance between SBBN and the CBR is spectacular.

Tension between the data and SBBN arises with ^{4}He. In Figure 3 are shown the BBN-predicted Y_P versus y_D relations for SBBN ($N_\nu = 3$) as well as for two variations on SBBN ($N_\nu = 2$ and 4). Also shown in Figure 3 are the primordial abundances of D and Y_P adopted here; see Sec. 3.1 and Sec. 4. Given the very slow variation of Y_P with η, along with the very high accuracy of the SBBN-abundance prediction, the primordial abundance is tightly constrained: $Y_P^{SBBN} = 0.248 \pm 0.001$. Agreement with the adopted value of $Y_P^{OSW} = 0.238 \pm 0.005$ is only at the $\sim 5\%$ level. This apparent challenge to SBBN is also an opportunity.

As already noted, while the ^{4}He abundance is insensitive to the baryon density, it is very sensitive to a nonstandard early expansion rate. Given the *pair* of primordial abundances $\{Y_P, y_D\}$ inferred from the observational data, the standard model (SBBN: $N_\nu = 3$) can be tested and nonstandard models ($N_\nu \neq 3$; $S \neq 1$) can be constrained. As Figure 3 reveals, the current data favor a slower than standard expansion rate ($N_\nu < 3$). If both η and ΔN_ν are allowed to be free parameters, it is not surprising that the adopted primordial abundances of D and ^{4}He can be accomodated (D largely fixes η, while ^{4}He sets S). In Figure 4 are shown the 1-, 2-, and 3-σ BBN contours in the $\eta - \Delta N_\nu$ plane derived from the adopted values of y_D and Y_P. Although the best-fit point is at $\Delta N_\nu = -0.7$ ($S = 0.94$), it is clear that SBBN ($N_\nu = 3$) is not unacceptable.

6   BBN And The CBR

As for BBN, the CBR temperature anisotropy spectrum and polarization are also sensitive to the early-Universe (RD) expansion rate (see, e.g., Barger *et al.* [11], and references to related
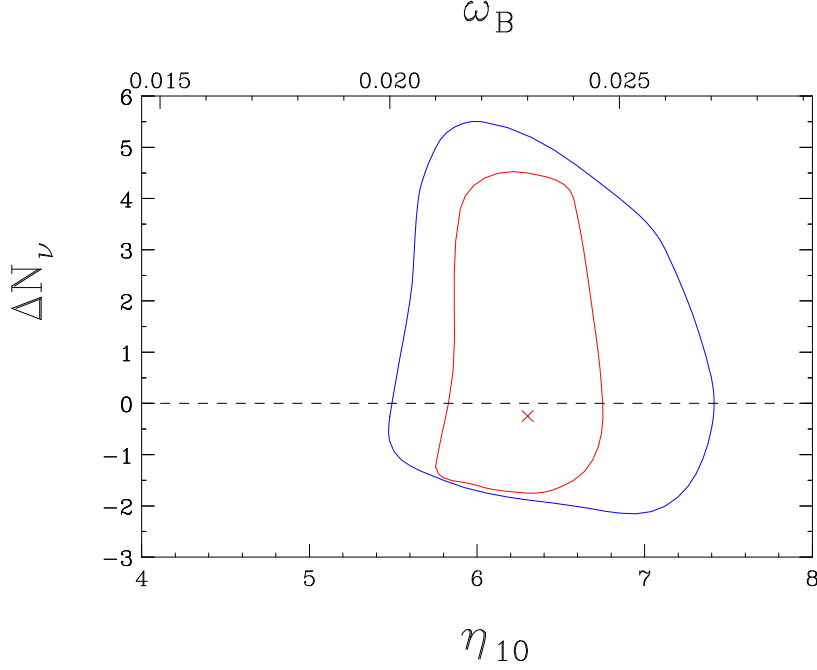
Figure 5: The 1- and 2-σ contours in the $\eta - \Delta N_\nu$ plane from the CBR (*WMAP*) data.

work therein). Increasing the baryon density increase the inertia of the baryon-photon fluid, shifting the positions and the relative sizes of the odd and even acoutic peaks. Changing the expansion rate (or, the relativistic particle content) of the early Universe shifts the redshift of matter-radiation equality so that there is a degeneracy between ΔN_ν (or S) and the total matter density $w_M \equiv \Omega_M h^2$. It is the HST Key Project determination of the Hubble parameter that helps to break this degeneracy, permitting the WMAP data to set constraints on the post-BBN, early-Universe expansion rate. Although the CBR temperature anisotropy spectrum is a less sensitive probe of the early-Universe expansion rate than is BBN, the WMAP data may be used to construct likelihood contours in the $\eta - \Delta N_\nu$ plane similar to those from BBN in Figure 4. These CBR-derived contours are shown in Figure 5; note the very different ΔN_ν scales and ranges in Figures 4 and 5. As is the case for BBN, the "best" fit value for the expansion rate is at $S < 1$ ($\Delta N_\nu < 0$), but the CBR likelihood distribution of ΔN_ν values is very shallow and the WMAP data is fully consistent with $S = 1$ ($\Delta N_\nu = 0$).

Comparing Figures 4 and 5, it is clear that there is excellent overlap between the $\eta - \Delta N_\nu$ confidence contours from BBN and those from the CBR (see Barger *et al.* [11]). This nonstandard variant of SBBN ($S \neq 1$) is also consistent with the CBR. In Figure 6 (from Barger *et al.* [11]) are shown the confidence contours in the $\eta - \Delta N_\nu$ plane for a joint BBN – CBR fit. Again, while the best fit value for ΔN_ν is negative (driven largely by the adopted value for Y_P), $\Delta N_\nu = 0$ ($S = 1$) is quite acceptable.

7 Summary And Conclusions

Adopting the standard models of cosmology and particle physics, SBBN predicts the primordial abundances of D, ^{3}He, ^{4}He, and ^{7}Li, which may be compared with the observational data. Of the light nuclides, deuterium is the baryometer of choice, while ^{4}He is an excellent chronometer. The universal density of baryons inferred from SBBN and the adopted primordial D abundance: $\eta_{10}(\text{SBBN}) = 6.10^{+0.67}_{-0.52}$, is in excellent agreement with the baryon density derived largely from CBR data [10]: $\eta_{10}(\text{CBR}) = 6.14 \pm 0.25$. For this baryon density, the predicted primordial abun-
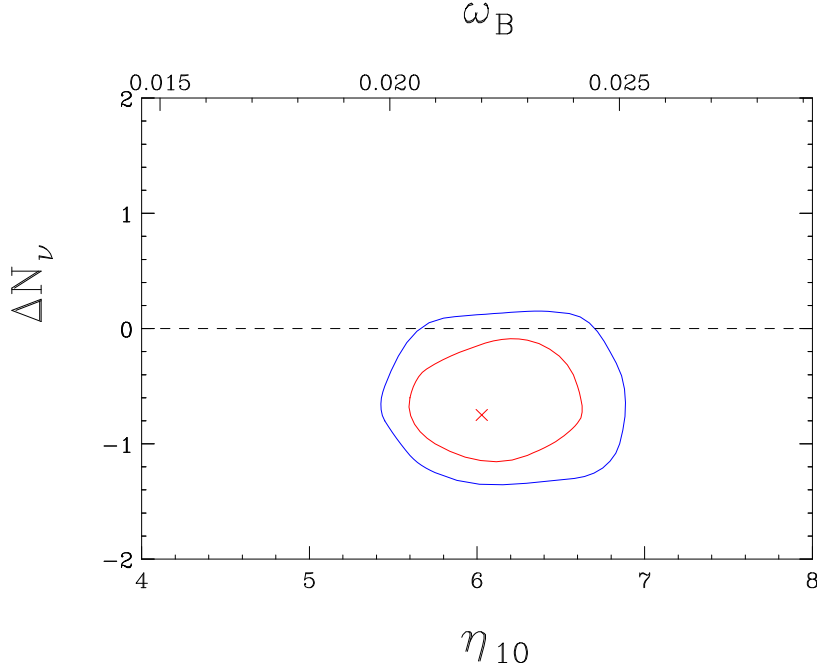
Figure 6: The 1- and 2-σ contours in the $\eta - \Delta N_\nu$ plane for the joint BBN – CBR (*WMAP*) fit.

dance of ^{3}He is also in excellent agreement with the primordial value inferred from observations of an outer-Galaxy H II region (Bania *et al.* [5]). In contrast, the SBBN-predicted mass fraction of ^{4}He for the concordant baryon density is $Y_P^{SBBN} = 0.248 \pm 0.001$, while that inferred from observations of recombination lines in metal-poor, extragalactic H II regions [9] is lower: $Y_P^{OSW} = 0.238 \pm 0.005$. Since the uncertainties in the observationally inferred primordial value are likely dominated by systematics, this $\sim 2\sigma$ difference may not be cause for too much concern. If it survives the accumulation of new data, this tension between D and ^{4}He (or between the CBR-determined baryon density and ^{4}He) can be relieved by a variation of the standard model in which the early, RD Universe expands more slowly than it should according to the standard model. If *both* the baryon density and the expansion rate factor are allowed to be free parameters, BBN (D, ^{3}He, and ^{4}He) and the CBR (WMAP) agree (at 95% confidence) for $5.5 \leq \eta_{10} \leq 6.8$ ($0.020 \leq \Omega_B h^2 \leq 0.025$) and $1.65 \leq N_\nu \leq 3.03$. More D and ^{4}He data, along with a better understanding of systematic errors, will be crucial to deciding whether the source of this tension is inaccurate data (and/or data analysis) or is the first hint of new physics.

The wealth of observational data accumulated in recent years have propelled the study of cosmology from youth to maturity. In the current, data-rich era of cosmology, BBN continues to play an important role. The spectacular agreement of the baryon density inferred from processes occurring at widely separated epochs confirms the general features of the standard models of cosmology and particle physics. The tension with ^{4}He provides a challenge, along with opportunities, to cosmology, to astrophysics, and to particle physics. Whether the resolution of the current challenge is observational or theoretical, the future is bright.

Acknowledgments

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